Selective Coordination versus Arc Flash - The Great Debate and Update

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Abstract - This paper will briefly cover Selective Coordination requirements as required in the National Electrical Code. Then protective device operation and selection with regard to code mandated full fault current range Selective Coordination will be discussed. Various aspects of Arc Flash Energy will be outlined. The concern of increased Arc Flash energy when code mandated Selective Coordination over the entire calculated available fault current range including a maximum 3 phase bolted fault will be covered. Included will be a discussion of why emergency systems, legally required standby systems and health care essential systems there were no real world problems associated with the previous partial fault current range selective coordination. The following two alternative proposals to modify full fault current range selective coordination for 600 volt and below equipment will be covered: 1) limiting selective coordination to 0.1 seconds and above, or 2) Full selective coordination except for the following cases: a) where arc flash energy levels at main ANSI C37 switchgear exceeds 40 cal/cm2 and b) where for other low voltage distribution and control equipment, other than ANSI C37 switchgear, arc flash energy levels exceeds 8 cal /cm2.

In addition, new circuit breaker and equipment designs and options available to achieve both Selective Coordination as well as reduced Arc Flash energy will be reviewed.

An update of some of the other alternatives that governmental bodies have taken regarding the adoption of the 2005 or 2008 NEC with modification of selective coordination requirements will be summarized.

Index Terms — Arc Flash, Selective Coordination, Flash hazard analysis, incident energy, National Fire Protection Agench (NFPA) 70E.

I. INTRODUCTION

Selective coordination first became a requirement in the National Electrical Code (NEC) in Article 620, “Elevators, Dumbwaiters, Escalators, Moving Walks, Wheelchair Lifts, and Stairway Chair Lifts” of the 1996 National Electrical Code (NEC) [1] . Section 620.62 specifically required that overcurrent-protective devices in each disconnecting means be selectively coordinated with any other supply side overcurrent-protective devices, where more than one driving machine disconnecting means is supplied by a single feeder. The NEC further expanded the requirement for selective coordination in 2005 as part of Article 700, “Emergency Systems”, and Article 701 for ”Legally Required Standby Systems” in Sections 700.27 and 701.18 entitled “Coordination”. These additions indirectly expanded selective coordination to “Essential electrical systems of Health Care Facilities” with the reference from section 517.26, “Application of Other Articles” in article 517, “Health Care Facilities”. This section requires meeting the requirements of Article 700 except as amended by Article 517. Since the Article 700.27 requirement for selective coordination was not amended in Article 517, it then automatically became applicable for Health Care facilities essential systems too.

Article 700, 701 and 708 all use the following statement modified for each specific article. “...system(s) overcurrent devices shall be selectively coordinated with all supply side overcurrent protective devices.” The following exception is only in Article 700 and 701.

Exception: Selective Coordination shall not be required in (1) or (2).

(1) Between transformer primary and secondary overcurrent protective devices, where only one overcurrent protective device or set of overcurrent protective devices exist on the transformer secondary.

(2) Between overcurrent protective devices of the same size (ampere rating) in series.

The 2008 NEC [3] added the requirement for selective coordination into the new Article 708, “Critical Operations Power Systems (COPS)”. Section 708.54, “Coordination”, requires that COPS overcurrent devices shall be selectively coordinated with all supply side overcurrent Devices. In addition, Article 708.52, “Ground-Fault Protection of Equipment”, requires that where ground-fault protection is required to be provided for operation of the service disconnecting means or feeder disconnecting means as specified in 230.95 or 215.10, an additional step of ground-fault protection shall be provided in all next level feeder disconnecting means downstream toward the load. The additional levels of ground-fault protection shall not be installed on electrical systems that are not solidly grounded-wye systems with greater than 150 volts to ground but not exceeding 600 volts phase-to-phase. Under 208.52(D), “Selectivity”, the requirement for the ground-fault protection for operation of the service and feeder disconnecting means shall be fully selective such that the feeder device but not the service device, shall open on ground faults on the load side of the feeder device. A six-cycle minimum separation between the service and feeder ground-fault tripping bands shall be provided. Operating time of the disconnecting devices shall be considered in selecting the time spread between these two bands to achieve 100 percent selectivity. The design engineer should note this requirement is for 6 cycle minimum separation between the two tolerance bands of the settings and NOT between the nominal settings. In addition, smaller breakers may open in less than ¾ of a cycle while larger circuit breakers and bolted pressure switches may take multiple cycles because of the larger mass to open and clear a fault.

NEC Article 100 Definitions defines Coordination (Selective) as follows:

"Localization of an overcurrent condition to restrict outages to the circuit or equipment affected, accomplished by the choice of overcurrent protective devices and their ratings or settings." Or simply put, only the overcurrent device directly protecting the circuit having an overcurrent condition should open. It should be noted that the Code Making Panel, CMP-13 committee responsible for NEC Articles 700 and 701 has stated that selective coordination shall apply throughout the current range including bolted three phase faults.

II. OVERCURRENT PROTECTIVE DEVICE OPERATION

As discussed in a previous paper presented at 2007 Electric West, "2005 NEC Selective Coordination Design Issues"[4], in order to properly design a selectively coordinated system, the design Professional Engineer must have an understanding of how the various overcurrent protective devices, such as, Molded Case Circuit Breakers (MCCBs), Insulated Case Circuit Breakers (ICCBs), Power Circuit Breakers (PCBs) and Fuses operate. The following is a brief discussion of these devices in relationship to low voltage (600 volts and below) selective coordination.

When applying overcurrent protective devices such as MCCBs, ICCBs, PCBs, and Fuses, these devices must have a voltage rating and interrupting capacity equal to or greater than the system voltage and available fault current at its point of application in the electrical distribution system. For the purposes of determining selective coordination for low level overloads or low level fault currents (typically below 10 times the device rating) only the minimum time band of the upstream device "A" must be reviewed to ensure that it does not overlap the maximum time band of the downstream device "B". This information can typically be determined from the published time –current curves of the devices as shown in Figures 1A and 1B.

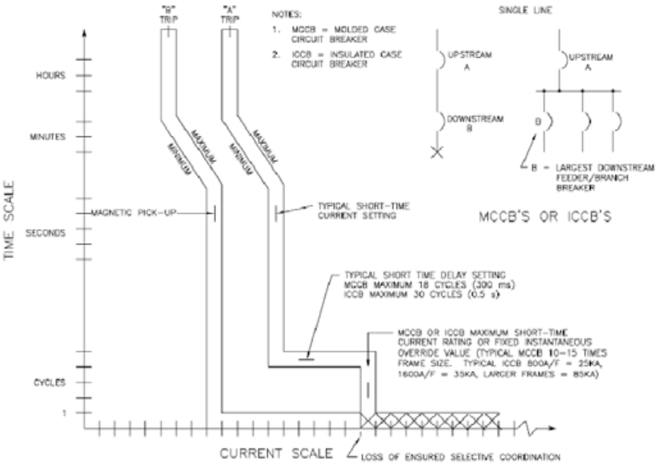


Fig. 1A: Molded Case Circuit Breaker (MCCB) and Insulated Case Circuit Breaker (ICCB) Time Current Characteristic Curves.

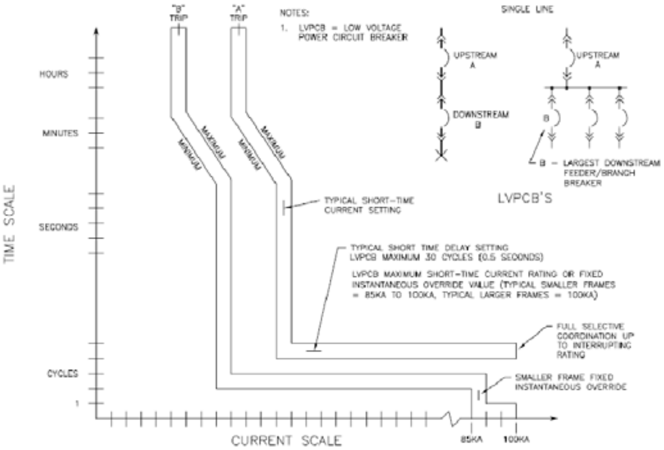


Fig. 1B: Power Circuit Breaker (PCB) Time Current Characteristic Curves.

A. *Low-Voltage Circuit Breaker Interrupting and Short-Delay Rating*

A key difference between a circuit breaker and a fuse is the ability of the circuit breaker to open and close the circuit multiple times which is made possible through the use of contacts, levers and springs that enable the breaker to carry currents without opening unless told to do so by a trip mechanism. The contacts of a circuit breaker are held closed via levers and springs to some maximum value. Under high fault conditions, these higher currents and associated magnetic fields place stresses and forces on the circuit breaker. For MCCBs, these magnetic forces generated by the higher fault currents could separate (tease) the contacts open, thus the tripping mechanism is designed to initiate a full spring driven instantaneous opening of the contacts. The ability of the circuit breaker to keep its contacts closed while fault currents are flowing defines the short delay rating of the circuit breaker. It is a goal of selective coordination for line side devices to keep their contacts closed while the load side breaker directly upstream from the fault, operates. There is a certain duration, based on the construction of the circuit breaker, that a circuit breaker can keep its' contacts closed for a specified value of fault current. When these short delay current or time values are exceeded, the circuit breaker WILL open instantaneously (with no intentional time delay). How long the circuit breaker can hold these high currents is dependent upon the construction of the device. IEEE standard 1015-2006 [5] defines "withstand rating" as the "maximum root mean square (rms) total current that a circuit breaker can carry momentarily without electrical, thermal or mechanical damage or permanent deformation." This publication also defines the interrupting rating of the breaker as "The highest current at rated voltage that a device is intended to interrupt under standard test conditions." On the other hand this reference refers to the short-time rating of the breaker as "A rating applied to a circuit breaker that, for reason of system coordination, causes tripping of the circuit-breaker to be delayed beyond the time when tripping would be caused by an instantaneous element." In other words the device's ability to stay closed and NOT open the circuit immediately under fault conditions. For the purposes of this article, the short-time rating of the circuit breaker will be broken down into two facets:

1) Short-Delay current rating –The maximum current magnitude under a fault condition for which the circuit breaker can stay closed.

2) Short-Delay time rating – The amount of intentional time delay in the tripping of a circuit-breaker between the overload and the instantaneous pickup setting.

The maximum short-delay time is the maximum amount of time the breaker can keep its contacts closed under the fault condition. If two breakers are in series, to obtain selective coordination, the upstream or line side circuit breaker must have a short-delay current setting above the actual fault current on the load side of any downstream breaker. In addition, the upstream circuit breaker has to have a short-delay time capability long enough to allow the down stream breaker to open and clear the fault condition.

B. *Molded Case Circuit Breakers (MCCB)*

Standard Molded Case Circuit Breakers (MCCBs) are manufactured and tested to UL-489, "Molded-Case Circuit Breakers, Molded-Case Switches and Circuit-Breaker Enclosures". MCCBs have over-center toggle mechanisms and either a thermal-magnetic or electronic trip unit. The thermal magnetic trip unit is such that the magnetic pick-up maximum setting is approximately 10 times the trip rating. The electronic trip unit is typically furnished with a fixed instantaneous override of approximately 10 to 15 times the breaker frame rating, or trip unit rating. Thus for MCCBs with either thermal-magnetic or electronic trip units, for any load side fault above these levels, the breaker will open instantaneously. The exact magnitude of current which will cause the MCCB to open instantaneously, will vary by

1) Circuit breaker manufacturer
2) Circuit breaker frame rating
3) Type of trip unit
4) Type/vintage of MCCB
5) Manufacturer's curve tolerances.

For purposes of this paper, it will be assumed that the current magnitude which will cause MCCBs with electronic trips to open instantaneously is 13 times the frame rating – its fixed instantaneous override. The manufacturer's actual data should be used to determine this value. Typically for MCCBs, once the magnetic pick-up or fixed instantaneous override is exceeded, the circuit breaker will open, with an opening time of 1 cycle or less. [See Figure 1A.]

Although short-time "ratings" for MCCBs are not covered in IEEE STD 1015, some MCCBs are equipped with electronic trip units that have adjustable "short delay" functions. However, they typically also have either an adjustable instantaneous trip (typically with a maximum setting of 10 times trip ampere) or a fixed instantaneous override (of a maximum of approximately 13 to 15 times the frame ampere rating). When the electronic trip is in the short-time pickup range (below 13 to 15 times frame size), they can typically be adjusted up to a maximum short-time delay setting of approximately 18 cycles (0.3 seconds).

Per UL-489 standard, current limiting circuit breakers have characteristics that, when operating within their current-limiting range, limit the let-through I2t to a value less than the I2t of a ½ cycle wave of the symmetrical prospective current. Current Limiting Circuit Breakers achieve this by opening their contacts very rapidly, such that their IPeak let through current is reduced to a value much lower than the IPeak current available from the system at the MCCB's point of application.

C. *Insulated Case Circuit Breakers (ICCB)*

Insulated Case Circuit Breakers (ICCBs) are also manufactured and tested to UL-489, however, they usually have a two-step stored energy mechanism and increased short-time capabilities. These breakers are typically available in 800A, 1600A, 2000A, 2500A, 3000A, 4000A and 5000A frame sizes. Although they may have high interrupting ratings, the typical instantaneous override values for ICCBs are 25kA to 35 kA for the smaller frames and up to 85kA for the larger frames. Maximum short-time delay capability is generally up to 30 cycles (0.5 seconds). [See Figure 1A.]

D. *Low Voltage Power Circuit Breakers (PCB)*

Low-Voltage Power Circuit Breakers (PCBs) are manufactured and tested to the UL-1066 Standard and ANSI C37 standards and have a two-step stored energy mechanism. PCBs are typically available in 800A, 1600A, 2000A, 2500A, 3000A, 4000A and 5000A frame sizes. However even the smaller 800A frame size is available with very high short-time current ratings of approximately 85kA to 100 kA. PCBs are capable of keeping their contacts closed for up to 30 cycles of fault current, at levels up to their maximum short-time current rating. Thus PCBs can normally provide selective coordination with relative ease when in series with each other, or when supplying downstream MCCBs or ICCBs. [See Figure 1B.]

E. *Low Voltage Fuses*

Low-Voltage fuses typically have time-current curves published for “Minimum Melt Time” and “Total Clearing” time. When these do not overlap, then the fuses will selectively coordinate in the range shown, but NOT necessarily in the higher fault range typically above 10 to 15 times the fuse rating. [See Figure 1C.]

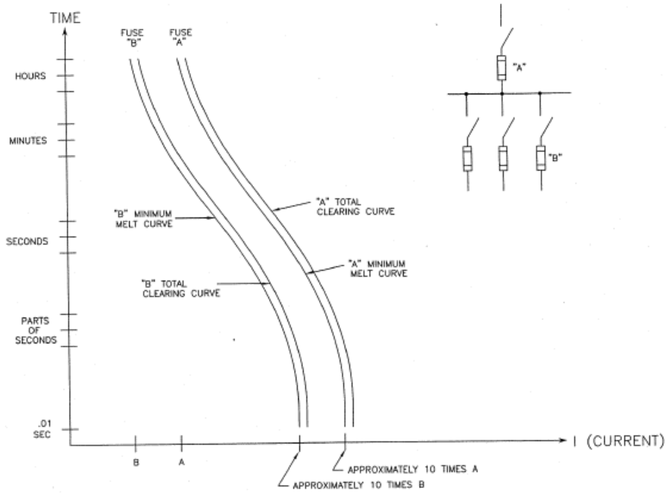


FIGURE 1C

TYPICAL FUSE TIME VS CURRENT CURVES

Fig. 1C: Low Voltage Fuse Typical Time Current Characteristic Curves.

It should be recognized that when utilizing these curves, the fuses are NOT in the current-limiting mode, thus the let-through I2t is NOT limited to a value less than the I2t of a ½ cycle wave of the symmetrical prospective current. Typically to determine the IPeak (IP) let-through of a fuse, a chart of “Prospective IRMS versus IP let-through” or manufacturer data charts must be utilized. [See Figure 1D]. To determine if fuses of a specific manufacturer are selectively coordinated across all current ranges, a ratio selection chart of line type fuse versus load type fuse must be utilized. It should be noted these charts are for only the specific manufacturer of that brand fuse and cannot be utilized with other manufactures fuses. These charts were developed based on the test circuit X/R ratio.

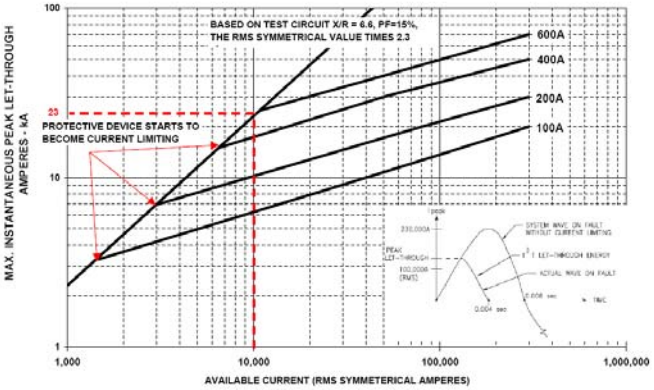


FIGURE 1D

PROSPECTIVE I_{rms} to I_{peak} LET-THROUGH

Fig. 1D: Prospective Irms to Ipeak Let-Through.

F. *Effect of X/R Ratio*

The interrupting rating for low-voltage circuit breakers is based on test circuits with a Power Factor (PF) resulting in a Reactance (X) to Resistance (R) ratio (X/R) as indicated in Table 1. The test circuit for Fuses typically utilizes an X/R ratio of 6.6 resulting in a system I peak (IP) to Irms ratio of 2.3.

TABLE I

TEST CIRCUIT POWER FACTORS

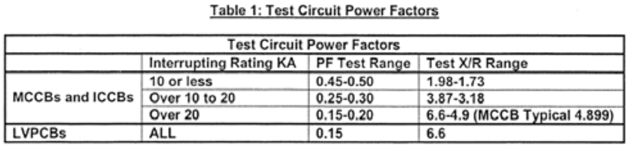


Table 1: Test Circuit Power Factors

Test Circuit Power Factors			
	Interrupting Rating KA	PF Test Range	Test X/R Range
MCCBs and ICCBs	10 or less	0.45-0.50	1.98-1.73
	Over 10 to 20	0.25-0.30	3.87-3.18
	Over 20	0.15-0.20	6.6-4.9 (MCCB Typical 4.899)
LVPCBs	ALL	0.15	6.6

The test circuits for circuit breakers and fuses with PF and X/R ratios as previously indicated were selected because in many cases they represent the real world conditions. For example, PCBs are typically utilized in applications such as service entrance switchgear, or in secondary switchgear connected to unit substations. Thus, because the utility transformer or unit substations transformer has a large reactance (X) component, the X/R ratio of 6.6 or below is typical of many of these applications. By contrast, smaller MCCBs having less than a 10 kA interrupting rating, typically are applied in branch circuit panelboards being supplied by long lengths of conductors having higher resistance (R), thus reducing the X/R ratio.

As the system available X/R ratio gets higher, the ratio of available first ½ cycle peak current, to the system rms available fault current, becomes higher, reaching a maximum ratio of 2.823 at zero power factor. The higher the X/R ratio (lower fault PF), the harder it is for a circuit breaker to interrupt the fault condition. There are circuit breaker derating tables for interrupting ratings which should be utilized when the actual system X/R exceeds the test circuit X/R as indicated in Table 2.

TABLE 2
TEST CIRCUIT POWER FACTORS

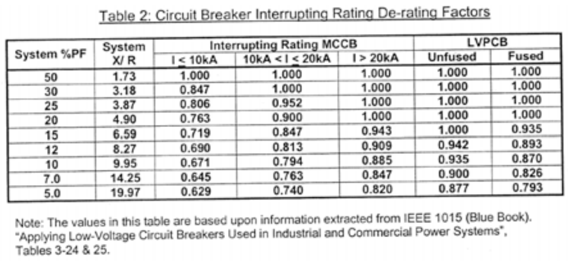


Table 2: Circuit Breaker Interrupting Rating De-rating Factors

System %PF	System X/ R	Interrupting Rating MCCB			LVPCB	
		I ≤ 10kA	10kA < I ≤ 20kA	I > 20kA	Unfused	Fused
50	1.73	1.000	1.000	1.000	1.000	1.000
30	3.18	0.847	1.000	1.000	1.000	1.000
25	3.87	0.806	0.952	1.000	1.000	1.000
20	4.90	0.763	0.900	1.000	1.000	1.000
15	6.59	0.719	0.847	0.943	1.000	0.935
12	8.27	0.690	0.813	0.909	0.942	0.893
10	9.95	0.671	0.794	0.885	0.935	0.870
7.0	14.25	0.645	0.763	0.847	0.900	0.826
5.0	19.97	0.629	0.740	0.820	0.877	0.793

Note: The values in this table are based upon information extracted from IEEE 1015 (Blue Book). "Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems", Tables 3-24 & 25.

With regards to low voltage circuit breakers, the electronic trip unit's instantaneous pickup responds to system peak current. To ensure selective coordination is obtained, a short circuit and coordination study should be performed to determine the available fault current levels, and X/R ratios, at various key points where protective devices are located in the electrical distribution system.

It should also be noted, that the point at which current limiting circuit breakers and fuses become current limiting are typically shown on the "Prospective Irms to IP Let-Through" charts. This point changes depending on the X/R ratio of the actual circuit. Thus the actual circuit X/R ratio will determine when the current limiting circuit breaker or fuse becomes current limiting. Note that the degree of the current limiting effect becomes greater as the available fault current increases from the initial current limiting thresh-hold. In order for two fuses to be selectively coordinated, the I2t let through energy of the load side fuse must be less than that which would be required to start to melt or melt the line side fuse link. [See Figure 1D].

III. PROTECTIVE DEVICE SELECTION

A. *General Discussion*

For the purposes of this discussion, a typical partial single line of a small emergency or legally required standby system as shown in Single Line Figure 2 will be reviewed. This drawing indicates protective devices initially chosen based on load requirements prior to a selective coordination study. The normal 480 volt system consists of a 1000 kVA utility supply or unit substation transformer, to a main 1200 Ampere Frame (AF), 1200 Ampere Trip (AT) main molded case circuit breaker (PD1). This 1200AF/1200AT MCCB feeds switchboard bus M-SWB-1200A. From this switchboard, there is a 400AF/400AT feeder MCCB (PD2) supplying the normal side of a 400A Automatic Transfer Switch (ATS). The load side of the ATS feeds an emergency distribution panelboard (EMD) with 4-100AF/100AT MCCBs. A typical 100AF/AT feeder breaker, (PD4), supplying an emergency branch panelboard EMB is shown which in turn supplies switchboard EMB.

The emergency side of the ATS is supplied by a 500 kW Generator (0.8 Power Factor) connected to an emergency switchboard (EM-SWB). An 800AF/800AT main MCCB (PD6) in turn feeds a 400AF/400AT MCCB (PD3) which in turn feeds from EM-SWB to the emergency side of the ATS.

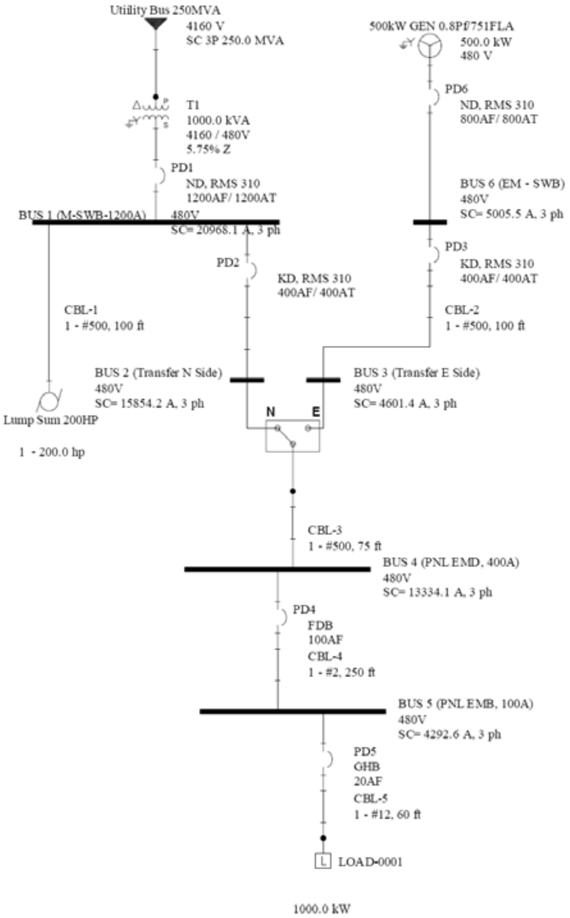


Fig. 2: Single Line Diagram of Sample System.

Single line Figure 2 shows the calculated fault currents based on the ATS supplying power from the normal utility power source. It is important to remember that the selective coordination study must be conducted as per the largest available fault current from either the normal or emergency supply.

An important clarification that the design engineer must consider is the answer to a question that continues to be debated by many. That question is the interpretation of “all supply side overcurrent protective devices” found in the NEC. The reason this is important is because the answer to this question will identify whether the design engineer must obtain total selective coordination up through the emergency side of the power distribution system to the Generator AND up through the normal side of the power distribution system to the utility. The answer to this question is only obtainable from the local Authority Having Jurisdiction (AHJ). As per the 2008 NEC Article 100, the AHJ is defined as an organization, office or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

Some common interpretations are as follows:

1. All overcurrent protective devices on the load side of the ATS have to be selectively coordinated as well as all overcurrent protective devices on the emergency line side supply.

2. All overcurrent protective devices on the load side of the ATS have to be selectively coordinated as well as all overcurrent protective devices on the emergency line side supply and only the normal side overcurrent protective device feeding the ATS.

3. All overcurrent protective devices on the load side of the ATS have to be selectively coordinated as well as all overcurrent protective devices on the emergency line side supply and all the normal side overcurrent protective devices feeding the ATS that are in series up to and including the normal side main overcurrent device.

Local AHJs can take into consideration the historical impeccable track record of design methods of engineers of legally required standby systems and health care essential systems which have operated through history with no documented cases of accidents or deaths associated with lack of total selective coordination. In addition to the most common reason of power loss being that due to utility outages, issues within the power distribution system are normally not the 3-Phase Bolted Fault on which total selective coordination is focused. It is an industry accepted fact that in real world experience, the most common overcurrent conditions are actually overloads, followed by phase to ground arcing faults of lower magnitudes or single phase to phase arcing faults. Historical practices of power system design engineers achieved impeccable performance of their protective devices because these devices addressed the clear majority of all electrical fault currents which are typically up to 13 times the larger device ratings up stream of a group of smaller protective devices.

The following offers some industry experience related to this topic. IEEE technical publications substantiate the fact that most faults are arcing lower level faults.

"Bolted short circuits are very rare, however, and the fault usually involves arcing and burning. Under these conditions, fault currents may be much lower than bolted fault values and may present special problems of detection and isolation." [6]

"In calculating the maximum short-circuit current, it is assumed that the short-circuit connection has zero impedance (is "bolted") with no current-limiting effect due to the short circuit itself. It should be recognized, however, that actual short circuits often involve arcing, and variable arc impedance can reduce low-voltage short-circuit current magnitudes appreciably." [7]

"Any of these four geometric variants may or may not be bolted faults, that is, short circuits in which the conductors are shorted together with essentially no external impedance. In the real world, most faults involve some external impedance (and in fact arcing introduces external resistance), but protection engineers usually consider bolted faults as the worst case for determining fault current magnitude." [8]

"Due to the prefabricated nature of busways, bolted faults are rare." [9]

"In contrast to the bolted fault, arcing faults can occur at any time in the life of a system. Although many individual factors may initiate an arcing fault, they generally involve one or more of the following: loose connections, foreign objects, insulation failure, voltage spikes, and water entrance. Because of the resistance of the arc and the impedance of the return path, current values are substantially reduced from the bolted fault level." [10]

There are many other design features that engineers employ to improve the reliability of electrical power systems for emergency, legally required standby systems, health care essential systems and COP systems. One such design decision is to include a generator as an alternate emergency source feeding the emergency loads through an automatic transfer switch. The emergency system is normally not energized, thus it is much rarer to have a fault on the line side of the ATS. When supplied from the generator, the available three-phase bolted fault currents are significantly lower than those available when supplied from the normal system (typically 10 times the generator full load rating). Thus the overcurrent protective devices chosen to selectively coordinate for the normal side may selectively coordinate for the lower fault currents from the emergency side. However, if the devices on the load side of the ATS have been significantly increased to meet normal available fault current selective coordination requirements, the ATS emergency line side devices may also be required to increase.

Most any instance of purported lack of selective coordination can be attributed to a few of the below causes:

1. Circuit breakers supplied during construction are left at minimum factory settings and not set per the coordination study during start-up.

2. Replacement circuit breakers not properly set when installed.

3. Ground fault equipment not specified on enough layers of series breakers such that a phase to ground fault much further downstream causes the opening of a main or first level

sub-feed breaker having ground fault equipment. It should be noted, that although in many cases, ground fault equipment is specified to be supplied on the main and first level feeder breakers, it is not necessarily specified on second, third or further additional series layers of circuit breakers or fused switches. This ground fault equipment is typically specified or in the case of COPS required to be selectively coordinated with adequate delay between ground fault equipment but rarely also required to be coordinated with downstream one-pole branch circuit breakers. The vast number of ground faults occur in loads connected on the branch circuit. These branch circuit breakers (without Ground Fault detection) will see these ground faults as normal phase current. Depending on the type of selected branch circuit breaker, in many cases, the upstream ground fault equipment can be set to allow the branch breaker to trip instantaneously before tripping an upstream circuit breaker feeding the panelboard, multiple panelboards or in some cases the service disconnect supplying the entire facility.

4. Ground fault equipment not field set per the coordination study.

It is very important to consider all aspects of the design to ensure a reliable system. It is also very important to communicate with your AHJ and your equipment supplier to ensure local requirements are met with properly selected equipment. It will be assumed here that the local AHJ has determined that the design must selectively coordinate up through both the normal and emergency sides of the ATS.

B. *Selection of Circuit Breakers*

The first step in the process to determine the devices required to meet the NEC total selective coordination requirements, after an accurate single line diagram has been obtained, is to perform a fault study. The fault study determines the available fault current at each piece of distribution equipment. All protective devices must be selected with adequate voltage, continuous current, trip ratings and interrupting capacity for the point at which they are applied in the electrical distribution system. Figure 2 illustrates the initial selection of typical overcurrent device ratings meeting these requirements prior to the selective coordination study.

It should be noted, that the interrupting capacity selected for the circuit breakers located on the load side of the ATS must be based on the highest available fault current from either source, emergency or normal. This highest available fault value from either source is also the value that must be utilized in the determination of selective coordination requirements.

The plotted curves in Figure 3 depicts the plotted curves of the system that was designed based on load and fault currents that are typically seen in electrical distribution systems. Curve PD-N1 illustrates selectivity in the lower current ranges except for a small overlap of curves between PD5 and PD2.

The process for total selective coordination, begins at the lowest point in the distribution system. Note the highest possible available fault current at the load side device is utilized to determine the overcurrent tripping response of the line side protective device. Thus when addressing coordination of devices PD4 and PD5, the calculated 4292.6A (rounded to 4.3 kA) of bolted three phase symmetrical RMS fault current at Panel EMB from the Normal source should be used as apposed to using the available 2979.2A (rounded to 3.0kA) of bolted three phase symmetrical RMS fault current available from the emergency generator source.

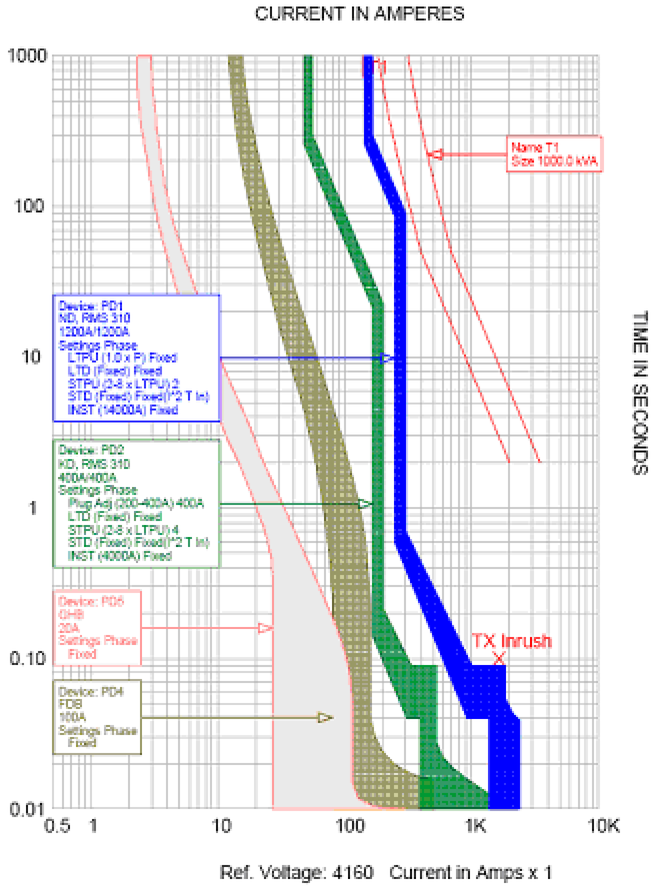


Fig. 3: Plotted curves for sample system designed based on load and fault currents that are typically seen in electrical distribution systems.

The 4.3 kA at EMB is used to see if the 100AF/100AT type FD circuit breaker, PD4, initially selected to feed EMB would trip on this available fault current level before the down stream 20A PD5 circuit breaker. It is evident, even without looking at the curves, based on the previous discussion of MCCB operations, that the 100AF/100AT circuit breaker would trip instantaneously at any current value above 13 x 100A or 1300A. This can also be determined from a review of the curves shown in CURVE PD-N1 Since the available fault current of 4.3 kA far exceeds this value, total selective coordination is NOT achieved. Thus we are presented with an issue where the available fault currents exceed the instantaneous over rides of both circuit breakers being applied. Determining which circuit breaker will open first is not possible from the data provided on typical TCC curves. The following options typically exist to resolve this problem:

1. Increase the withstand capabilities of the line side circuit protective device by selecting a larger frame circuit breaker for the line side MCCB that has an instantaneous override based on the larger frame but can be supplied with the required smaller trip size. Some manufactures are now offering these special type circuit breakers to meet selective coordination requirements. In many cases, the smallest trip size which can be furnished in the larger frame circuit breaker is not small enough to meet the existing cable and equipment bus rating. Therefore the cable size and equipment bus rating must be increased. This will typically require a revision of the fault study based on the larger cable size which will yield higher fault current values. NOTE the larger frame size circuit breakers may require physically larger panelboards and/or switchboards as well as increased cost.

2. Increase the withstand capabilities of the line side circuit protective device by changing from line side MCCBs to PCBs. If both main and feeder circuit breakers are changed to PCBs, this generally then leads to upgrading to ANSI C37 Low Voltage Switchgear with draw-out PCBs.

3. Change the combination of load side MCCB and line side MCCB to one that takes into consideration the presence of the arc impedance when the load side circuit breaker opens. This arc impedance reduces the current as seen by the line side circuit breaker to a value that will enable selective coordination. This type of information cannot be found on the Time Current Coordination (TCC) curves normally used in selective coordination studies. This information can only be determined by manufacturers test data. Each manufacturer who is publishing selective coordination data tables assembles this information based on their own test criteria. The engineer must understand that unlike the conventional TCC curves where trip curve could be compared between manufacturers and types of protective devices, there are no published selective coordination tables between circuit breakers or fuses of different manufacturer.

One manufacturer, such as Eaton Corporation, utilized existing UL standards in their testing and clearly indicates this in their published tables. It is important to understand how these tables were developed as you apply the products in the field. These tables are only applicable when the available fault current of the downstream circuit breaker exceeds that circuit breaker's instantaneous override or magnetic pick up levels. For all currents lower than that, the existing TCC curves may be used to identify proper selectivity. Time-current curves of the series circuit breakers under consideration still need to be reviewed to determine selective coordination for these lower current values.

4. Change the type of load side MCCB to a current limiting type.

5. Reduce the available fault current by increasing the impedance of the system by relocating equipment requiring longer cable runs.

6. Revise the single line diagram and divide larger loads into smaller loads with multiple ATS and fewer protective devices in series.

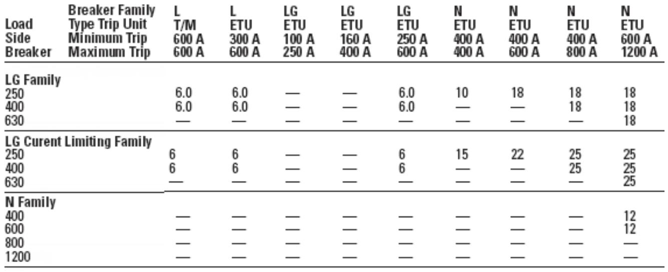
In this case, option number 3 is chosen and the data supplied by the manufacturer is used to determine that the up stream circuit breaker will selectively coordinate to meet the needs of this project. From the available tables, it was clear that no circuit breaker that can be supplied with as low as a 100A trip can selectively coordinate with the GHB downstream device with an available 4.3kA of bolted three phase fault. From these tables, it is determined that an LG (600AF) with an Electronic Trip Unit (ETU) having a trip range of 160A to 250A will selectively coordinate with the 20A GHB circuit breaker up to a value of 7.4 kA. With the change to a circuit breaker with a minimum setting of 160A trip, the design engineer must address protection issues on the feeder cable it must protect. The fact that the lowest available trip is 160A causes the design engineer to make a design change such that the feeder cable and EMB bus be increase to more than or equal to this rating. The cable must be changed from a #2 to 2/0 and the EMB panelboard bus increased from 100A to the next standard 225A rating. Now that the circuit has changed, the short circuit fault values must be re-calculated. The new 2/0 cable size increased the fault current at EMB to 6.4kA. The manufacturer tested selective coordination data indicates the LG with 160A trip will selectively coordinate with the GHB breaker to a value of 7.4kA, thus this is an acceptable combination.

The impact to this design thus far has been to increase the available fault current at Bus 5, panel EMB from 4.3kA to 6.4kA. This increase of available fault current required a change of electrical distribution products able to withstand it including the EMB panel from 100A to 225A and the feeder from a #2 to a 2/0.

Now the design engineer moves to the next layer of protection. Here the answer to the heavily debated question must be sought. If this project is located where the AHJ has interpreted "all supply sources" to include the normal 400A circuit breaker feeding the ATS, PD2, as well as the 1200A normal main circuit breaker, PD1, total selective coordination to the normal source and the emergency generator source must be met. Assuming this is the case, a similar process to that above ensues.

A quick review of the available fault current at EMD yields 13.3 kA which again is higher than 13 x 400A = 5200A instantaneous override setting of the 400A normal circuit breaker feeding the ATS. The design engineer must find an upstream circuit breaker that can withstand the current for a duration that will give the downstream device enough time to clear the fault. Again, because the data required to make this decision is not on the available TCC curves, the manufacture's tables are reviewed.

From Figure 4 it can be seen that for a 400A LG load side circuit breaker, an N Frame circuit breaker must be used. In this case, the 1200AF ND breaker with a 1000 Amp Sensor is selected and the long time pick-up is configured for 400Amps to match the needs of the distribution equipment. In this case, because of the flexibility of the electronic trip unit, the frame size was able to be increased and adjustments made to dial down the long time pick up such that the selected equipment would not have to be modified. The available bolted 3-phase fault current stayed the same but will remain on the distribution system for a longer duration to provide the downstream protective device enough time to clear the bolted three phase fault.

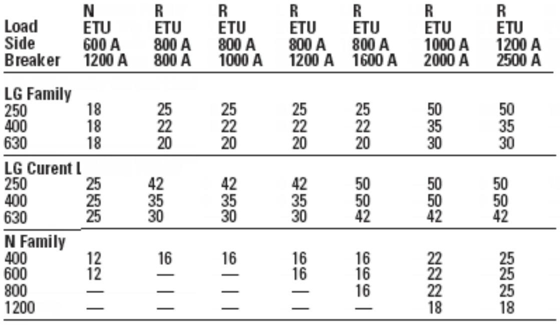


Load Side Breaker	Breaker Family Type Trip Unit Minimum Trip Maximum Trip	L T/M 600 A 600 A	L ETU 300 A 600 A	LG ETU 100 A 250 A	LG ETU 160 A 400 A	LG ETU 250 A 600 A	N ETU 400 A 400 A	N ETU 400 A 600 A	N ETU 400 A 800 A	N ETU 600 A 1200 A
LG Family										
250		6.0	6.0	—	—	6.0	10	18	18	18
400		6.0	6.0	—	—	6.0	—	—	18	18
630		—	—	—	—	—	—	—	—	18
LG Curent Limiting Family										
250		6	6	—	—	6	15	22	25	25
400		6	6	—	—	6	—	—	25	25
630		—	—	—	—	—	—	—	—	25
N Family										
400		—	—	—	—	—	—	—	—	12
600		—	—	—	—	—	—	—	—	12
800		—	—	—	—	—	—	—	—	—
1200		—	—	—	—	—	—	—	—	—

Fig. 4: Manufacture supplied selective coordination table.

Thus far in this design, we have changed a conductor size which increased the available fault current low in the distribution system. We've had to increase the ratings of the equipment due to the change of a downstream circuit breaker as well. We have also had to increase the frame size of an upstream circuit breaker to allow the bolted three-phase fault currents to persist longer on the distribution system so as to provide enough time for the downstream productive devices to clear the bolted three-phase fault.

Finally, on the normal source side of the system, the last layer of circuit protection must be reviewed and selectively coordinated. Protective devices PD1 and PD2 must meet the requirements. Similarly, the 21kA of available fault current at main switchboard SWB is over the 13 x 1200A = 15,600A instantaneous override setting of the normal 1200A main circuit breaker. The same process as above is followed. From Table 2, for the 400A N Frame circuit breaker, an R Frame circuit breaker can be selected. Thus the normal main 1200AF/1200AT type N frame circuit breaker must be changed to a 2500AF/1200AT type R frame circuit breaker with an optional programmable advanced ETU which will selectively coordinate with the load side N frame breaker for values up to 22 kA. See "Curves PD-N2 Normal Side revised MCCB Selective Coordination" for the final version of the selective coordination curves for this system.



Load Side Breaker	N ETU 600 A 1200 A	R ETU 800 A 800 A	R ETU 800 A 1000 A	R ETU 800 A 1200 A	R ETU 800 A 1600 A	R ETU 1000 A 2000 A	R ETU 1200 A 2500 A
LG Family							
250	18	25	25	25	25	50	50
400	18	22	22	22	22	35	35
630	18	20	20	20	20	30	30
LG Curent L							
250	25	42	42	42	50	50	50
400	25	35	35	35	50	50	50
630	25	30	30	30	42	42	42
N Family							
400	12	16	16	16	16	22	25
600	12	—	—	16	16	22	25
800	—	—	—	—	16	22	25
1200	—	—	—	—	—	18	18

Fig. 5: Manufacture supplied selective coordination table.

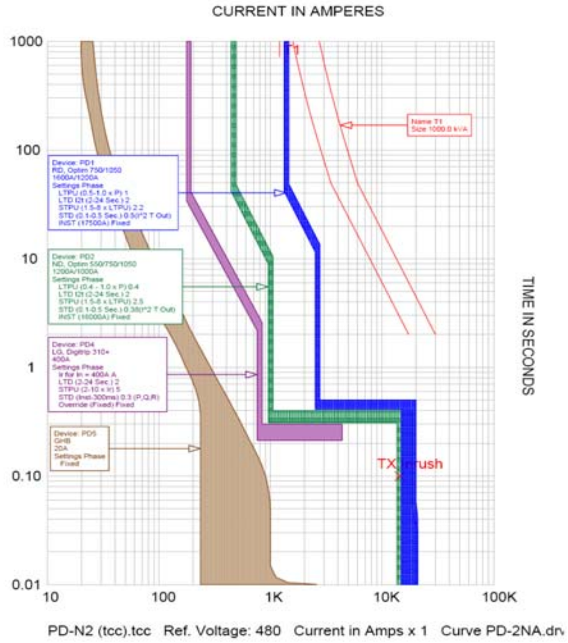


Fig. 6: Selectively coordinated system time current curves.

In this case, we successfully selected circuit breakers up through the normal side of this system to meet the needs of total selective coordination. If there were no MCCB combinations available which would selectively coordinate at the available fault current values indicated in the study, then one of the other methods discussed previously would have to be utilized. Note that mixing products between manufacturers or device types is not possible because the fault values are at levels that require test data to accurately determine proper selectivity.

Next a review of the emergency supply is made – reference "Single Line PD-E1 Emergency Side Initial MCCB Non-Selective Coordination" for calculated available short circuit values based on the generator supply. The 400AF/400AT type KD feeder circuit breakers on the line side of the ATS based on our assumption of an electronic trip instantaneous override being 13 times frame rating can selectively coordinate in the instantaneous range for up to 5200 amperes.

Since when on the emergency generator source the available fault current at Panel EMD is 4.4 kA, selective coordination is achieved in the instantaneous range. Note however, after reviewing the lower level fault range and overload range it was

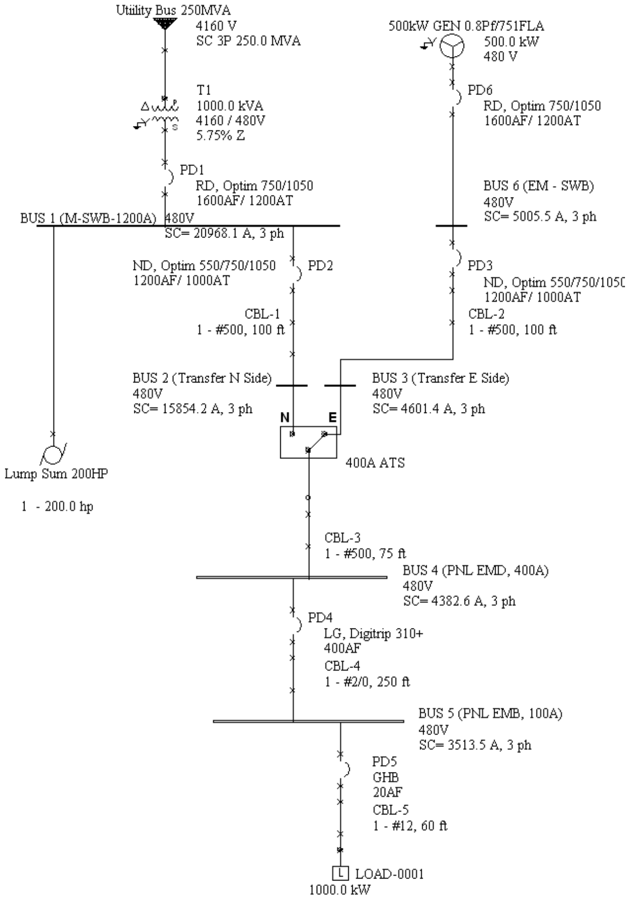


Fig. 7: Selectively coordinated system time current curves.

determined the devices do not selectively coordinate for these magnitudes. See "Curves PD-E1 Emergency Side Initial MCCB Non-Selective Coordination". Thus based on the devices which were previously revised on the load side of the ATS to meet selective coordination, the Emergency Line Side MCCBs also have to be revised. See Single Line PD-E2 and Curves PD-E2 for Emergency Side Revised MCCB Selective Coordination MCCBs chosen. Note these devices also have increased frames and optional programmable trip units.

Thus the appropriate changes to the design were able to be made by making changes to the system and selecting new circuit breakers.

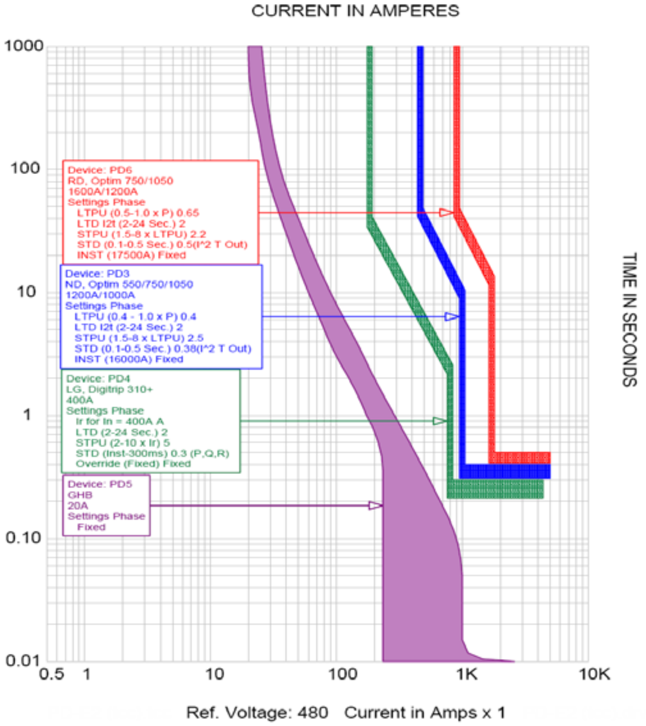


Fig. 8: Selectively coordinated system time current curves.

IV. ARC FLASH CONSIDERATIONS

Arc-Flash energy at any given point is dependent upon two key factors: The amount of available fault current at that point and the time that it takes for the upstream overcurrent protective device to open and clear the fault condition. As we just saw in the previous example selective coordination application, at times fault currents may increase while simultaneously increasing the time it takes to clear the fault condition. When designing to meet NEC Selective Coordination requirements, the engineer should ensure an Arc Flash study is performed and all equipment properly labeled.

As the short-time settings and/or short-time delay settings of upstream devices are increased and/or the instantaneous settings and/or instantaneous overrides increase, should a fault occur on the line side of a downstream circuit breaker and the load side of the upstream circuit breaker, the amount of Arc-Flash energy at the fault generally will be increased significantly. This increased Arc-Flash energy reduces the safety of operating and/or maintenance personnel should they cause or be present at the time of the fault and if no other provisions are in place in the design to address this issue. The higher level of Arc-Flash energy also increases the potential for major equipment damage resulting in fires and extended downtime.

A. *Arc Flash Energy*

NFPA 70E Standard for Electrical Safety in the Workplace defines “Flash Hazard” as “A dangerous condition associated with the release of energy caused by an electric arc.” Further it defines a “Flash Hazard Analysis” as “A study investigating a worker’s potential exposure to arc-flash energy, conducted for the purpose of injury prevention and the determination of safe work practices and the appropriate levels of PPE” (Personal Protective Equipment).

As stated above, the Arc-Flash energy at the fault point is dependent on two key factors:

1) The amount of available fault current at the point of the short circuit.

2) The time it takes for the upstream overcurrent protective device to open and clear the fault condition.

Thus as part of an arc-flash study, initial steps must include a short circuit study so as to determine the maximum and minimum available fault currents at the location under investigation. Next, as part of the arc-flash study, a coordination study must be performed to determine the opening time characteristics of the line side overcurrent device(s) protecting the circuit under investigation. Note that the arc flash energy is not necessarily at maximum at or near the bolted fault value of fault current. At the bolted fault levels of current, the overcurrent protective device typically opens faster than at lower values of fault current.

As a third part of the arc-flash study, when utilizing the NFPA 70E [11] table method, the type of work to be performed on the electrical components while energized has to be considered. For example, knowing when the work will be performed is very important. Will the work to be performed require opening a door over energized equipment to read a nameplate, or is it to drawout a circuit breaker or possibly change a fuse? The IEEE Std. 1584 method does not consider the type of work to be performed. Typically both the NFPA table method and IEEE method consider the working distance to be the distance from the workers face and torso and not the extremities, such as hands, arms, or feet to the point of the fault. The distance utilized in arc-flash studies is 18, 24 or 36 inches from the body to the faulted point under investigation, depending on the equipment class and voltage. The determination of required PPE is selected such that a qualified person is exposed to a maximum of 1.2 calories per centimeter squared which would result in the onset of a second degree burn. Another issue not part of the formal arc flash study is consideration for eyes and ears for the blast pressures and light from the arc-flash over 40 calories per centimeter squared. In addition, the arc-flash study should determine the proper PPE required to be utilized until an electrically safe work condition is determined to exist. This does not necessarily mean the opening of a circuit breaker or fused switch is acceptable for not having the proper PPE. The circuit still needs to be tested to confirm it is de-energized and properly grounded, locked out and tagged out to be deemed an electrically safe work condition per the NFPA 70E standard.

The IEEE Std. 1584 method of arc-flash calculations takes into account the fact that the arc-flash energy may be higher at reduced values of fault current because of the longer operating time of overcurrent protective devices. IEEE 1584 methods require that calculations be performed at both maximum and minimum available fault values. Thus when larger frame MCCBs with higher instantaneous settings or PCBs with higher short delay time settings are required to meet NEC selective coordination requirements typically, considerably higher arc flash energy results.

B. *Electrical Equipment Protection*

NEC Article 110.10 Circuit Impedance and Other Characteristics states “The overcurrent protective devices, the total impedance, the component short-circuit current ratings, and other characteristics of the circuit to be protected shall be selected and coordinated to permit the circuit-protective devices used to clear a fault to do so without extensive damage to the electrical components of the circuit. This fault shall be assumed to be either between two or more of the circuit conductors or between any circuit conductor and the grounding conductor or enclosing metal raceway. Listed products applied in accordance with their listing shall be considered to meet the requirements of this section.”

Thus it is required that the overcurrent protective devices operate quickly enough for all levels of available current to properly protect the conductors and other electrical equipment in the circuit. Most conductors have time current withstand curves indicating the various amount(s) of current the conductor can carry without damage for specific times. This is an inverse time-current relationship such that as the current goes up, the conductor material and its’ insulation will become damaged in a shorter period of time.

Most electrical equipment, not utilized for overcurrent protection, such as UL 1008 Automatic Transfer Switches or assemblies having bus bracing are tested by Underwriters Laboratories or other equivalent nationally accepted testing laboratory to meet either a “withstand” rating or “bus bracing” rating. Typically these tests are conducted at the maximum listed rating and for a specified length of time. For example, most ATSs and Switchboards, Panelboards, and Motor Control Centers bus bracing standards include testing for 3 cycles. Special approval of higher time ratings can be obtained at the same or reduced current values with special testing.

Thus to meet NEC 110.10 requirement that equipment be applied in accordance with their listing (withstand rating or bus bracing) and also provide higher time settings that maybe required for selective coordination, a need may exist for obtaining specially rated equipment and/or a redesign of the electrical distribution system to meet both of these NEC requirements.

C. *Arc Flash Study*

An arc flash study was performed per IEEE 1584 guidelines for the normal and emergency system with MCCBs that would have normally been supplied prior to the 2005 NEC mandated selective coordination requirements and then for the devices and settings that would have to be supplied to meet the NEC selective coordination requirements.

The results of the study are summarized in Table 3. As can be seen, the level of arc-flash for the selectively coordinated system is significantly greater than the initially designed system. In addition, instantaneous settings on the generator breaker and opening times of the normal and emergency MCCBs are longer than 3 cycles, which may require specially rated electrical circuit components and special bus bracing..

This increased arc-flash energy because of mandated NEC full selective coordination requires higher levels of PPE. In addition, the increased arc-flash energy significantly increases the possibility of increased equipment and/or facility damage.

TABLE 3
ARC FLASH CALCULATIONS RESULTS

		Initial Design		Total Selective Coordination	
Bus	Description	Incident Energy (Cal/cm2)	Required Protective FR Clothing Category	Incident Energy (Cal/cm2)	Required Protective Clothing Categor
1	PD1 LineSide	78	Dangerous!	78	Dangerous!
2	Transfer Normal Side	0.46	Category 0	12	Category 3
3	Transfer Emergency Side	0.92	Category 0	4.1	Category 2
4	Panel EMD, 400A	0.43	Category 0	3.9	Category 1
5	Panel EMB, 100A	0.16	Category 0	2.4	Category 1
6	EM - SWB PD6 Line Side	22	Category 3	22	Category 3

V. ENHANCING THE NATIONAL ELECTRICAL CODE

The NEC is a document that continues to offer an open-consensus process. Anyone can and many do submit proposals for consideration and the NEC continues to grow as an excellent document and resource as the most widely adopted code in the United States. States and/or local governing bodies do have the opportunity to modify the NEC to address local needs. There are numerous proposals being adopted by States and/or City or local governmental bodies which modify the selective coordination requirements. The most commonly heard proposals fall into two categories:

1) Allow the degree of selective coordination needed be the responsibility of the qualified person responsible for the project.

The State of Massachusetts was the first state to adopt such a proposal as an exception to the Articles in 700.27, 701.18 and 708.54 which require selective coordination as follows:

Exception No. 2: Where the system design is under the control of a licensed professional engineer engaged in the design or maintenance of electrical installations, the selection of overcurrent protective devices shall be permitted to coordinate to the extent practicable. The design shall be documented, stamped by the professional engineer, and made available for review by the authority having jurisdiction.

2) Proposals to modify the NEC requirement for selective coordination to only be required for above a specific time. The leading proposal is 0.1 seconds (6 cycles) and above. The State of Oregon recently adopted a proposal submitted by the National Electrical Contractors Association, Oregon Pacific-Cascade Chapter, as Statewide Alternate Method No. OESC 08-04 applying to Articles in 700.27, 701.18 and 708.54. this states the following: "The requirements in NEC 700.27, 701.18 and 708.54 for selective coordination may be demonstrated by providing a selective coordination study utilizing trip-curve data in the range of 0.1 seconds or more.

Substantiation for this proposal included:
1) "…selective Coordination is not always possible or practical for all fault current levels when protection is provided by molded case circuit breakers. The requirement for "total" selective coordination means that OCP devices must be coordinated for all faults, regardless of their magnitude or duration, including the most extreme case, the bolted fault. However, bolted three phase faults which rapidly generate extremely high current in the instantaneous range rarely occur in practice, except at start-up when interruption of power due to a lack of coordination is not likely to compromise safety…." "In order to achieve total short circuit selective coordination, the size of upstream overcurrent protective devices may need to be increased and/or time delay trip characteristics increased, thereby possibly increasing the arc flash hazard."

"Findings: By omitting the instantaneous range from the requirements for selective coordination, reasonable and effective safety can be achieved. Signing supervisors and engineers can use readily available and published time current curves to determine if a system is selectively coordinated to a substantial degree without having to rely on unregulated manufacturer testing data and inconsistent engineering and design practices."

VI. CONCLUSION

This paper has given background on the NEC selective coordination in Articles 700, 701 and 708 and NEC equipment withstand requirements, as well as NFPA 70E [11] arc flash requirements. As noted no real world problems were associated with the previous practice of selectively coordinating circuit breakers up to about 13 times their rating as allowed by the 0.1 proposal. A small typical system was discussed, showing how achieving total selective coordination required changing to larger frame breakers with advanced trip units and/or power circuit breakers. Arc Flash considerations were discussed in relationship to utilizing devices with higher instantaneous or short delay settings. Proposals to continue improving the NEC were discussed and involved modifying NEC selective coordination requirements to be determined by a qualified person or only requiring selective coordination at 0.1 seconds and above. It is apparent that mandated total selective coordination may result in higher levels of arc flash energy which may result in higher levels of equipment damage and/or increased injury and/or death to personnel.

VII. REFERENCES

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[8] IEEE Std 242-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems, Page 18

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[11] NFPA 70E, Standard for Electrical Safety in the Workplace, 2009 Edition

VIII. VITA

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